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DEVELOPMENT OF MOLDED, COATED FABRIC JOINTS

FABRIC CONSTRUCTION CRITERIA FOR A SPACESUIT ELBOW JOINT

Presented
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Introduction

Research on improvements in space suit design is being conducted into design and fabrication of a molded, coated fabric elbow joint capable of operating reliably at 8 psi internal pressure for extended periods of flexure. The overall design of the joint includes a.) selection of heat-settable fiber of sufficient strength, b.) choosing an optimum fabric construction, c.) a fatigue resistant, flexible coating and d.) a molding technique. Work on a fiber choice and the coating material has been reported previously with the resultant selection of a polyester yarn of DuPont type 56 Dacron and urethane coating system by Mobay Chemical Company. Final development of a method for molding the coated fabric composite is currently underway in a separate effort with NASA.

The specific purpose of this report is to define the relationships between yarn and weave parameters which lead to an optimum fabric construction for the 8 psi elbow joint.

Determination of Requisite Fabric Properties

Fabric properties deemed important to this application are discussed sequentially in the following. Firstly, minimum fabric strength is set by the operating internal pressure, 8 psi, and proof test pressure, 16 psi. To accommodate other factors, including extended fatigue life, tear resistance, and resistance to spontaneous crack propagation, the minimum strength should be modified to include a factor of safety of four at the normal working pressure. Spontaneous crack propagation occurs from an initiation point only

when fabric stress exceeds 50% of the ultimate breaking stress. A catastrophic joint failure can be expected to occur only under high stress conditions which may be avoided by design for the expected load.

The standard formula for hoop or circumferential tension caused by uniform internal pressure within a thin walled circular container is $T = Pd/2$, where T is fabric tension in lbs/inch, P is internal pressure in psi, and d is tube diameter in inches. For a 5 inch nominal diameter elbow joint operating at 8 psi, the fabric load would be 200 lbs per inch of fabric length (9080 grams per inch).

Axial tensile loading is separately constrained by the mechanical linkage system employed in the space suit. Even without this load support, the axial tension per inch circumference is one half the hoop tension. Thus, a fabric of uniform properties in transverse directions that withstands hoop tension requirements will also withstand axial tensile loads. The total axial load on a 5 inch nominal diameter joint is 157 lbs (71250 grams).

Thus, with a factor of safety of four at 8 psi, the ultimate fabric strength^{*} should be at least 4 x 20 or 80 lbs per inch width (36320 gms/in.). The reason for the unusual usage of mixed metric and English units will become apparent later.

The next fabric property under consideration is elongation. Tests conducted in 1981 by H. Vykukal at NASA Ames determined the following pressure versus joint diameter data as a desirable standard for design purposes:

<u>Pressure, Psi</u>	<u>Elbow Joint Diameter, Inches</u>
0	5.384
4	5.402
6	5.413
8	5.424
10	5.435

NOTE: See Appendix B for further discussion of yarn/fabric strength

While being slightly non-linear, the data follows approximately a straight line of slope 0.09% elongation per each psi in pressure increase. At 8 psi load, the elongation should be 0.7%, or for a 5 inch nominal diameter joint, the total circumferential length increase would be 0.11 inches.

The next fabric property under consideration is yarn spacing. To develop resistance to snagging and good appearance while avoiding excessive boardiness or stiffness due to overpacking yarns into the space allotted, yarn spacing must fall within a fixed range of cover factors. Cover factor^{*} is defined as the area covered by yarn in a woven fabric divided by the total area available. In practice, cover factor is multiplied by 28 to eliminate an empirical constant arising from the use of cotton count^{*} as a measure of yarn diameter. Cover factors should fall in the range of 22 through 32 to obtain an acceptable fabric. Above 32, adequate urethane coating penetration would be difficult to achieve. Secondly, yarn shrinkage during the molding/heat setting operation should be considered. Measured shrinkage at the setting temperature of 195⁰ C (383⁰ F) is 15% in a relaxed, unconstrained specimen. Letting K represent the original cover factor of the fabric as woven, K¹ the cover factor after heat setting, and s the fractional shrinkage, the relationship, $K^1 = K \times (1 - s)^{-2/3}$, expresses the change in cover due to heat setting. For 15% shrinkage, the cover increases by about 28%. Thus, to achieve a final cover of 29, for example, the initial cover should be about 23.

The original cover for a fabric of so called "square" construction, i.e. the yarn size and yarn spacing are the same in both primary woven fabric directions, warp and filling, is given by $K = N \sqrt{\text{denier}} / 36.5$. N is the number of yarns per inch in either warp or filling direction. Fabric production rate on the loom is inversely proportional to N. Denier^{*} is a measure of yarn linear density based upon the mass in grams of a 9000 kilometer length of yarn. Denier is uniformly

* NOTE: See Appendix A for a description of cover factor
See Appendix C for information on yarn count systems

accepted by fiber producers worldwide as the primary specification for yarn size.

The final fabric property to be covered is weave design. A plain weave is the obvious choice in terms of maximum tensile strength, appearance and support of the urethane coat. Additionally, weaving a tubular structure becomes more complicated, particularly at the fabric edges, if a weave design other than a plain weave is used. The plain weave offers a maximum number of yarn crossings and optimum fabric stability during the coating process.

Determination of Fabric Construction

The purpose of this section is to utilize the data presented in the previous section to arrive at a suitable fabric construction for the elbow joint. Fabric construction is determined by specifying the following parameters:

- 1.) Fiber type and size.
- 2.) Yarn size and twist in turns per inch.
- 3.) Yarn spacing in warp ends per inch and
filling picks per inch.
- 4.) Weave design

The yarn selected previously is DuPont Dacron polyester type 56. Types 55 and 26 are similar polyesters and all are readily available in 150 denier yarns with 30 or more filaments per yarn. A high level of producer roto-set is requested so that the yarns can be woven with no twist or no more than one or two turns per inch in the final yarn.

The final yarn size is determined through review of three factors:

- a.) $K = 23 = N \sqrt{\text{denier}/36.5}$, cover factor
- b.) $T_{\text{minimum}} = 9080 \text{ grams/inch} \times 4 \text{ factor of safety} =$
 $N \times (\text{denier}) \times 4.25$, strength minimum value

c.) 1% elongation occurs at a specific stress of 1 gram per denier, DuPont Bulletin D-243, therefore for 0.7% at 8 psi the loading should not exceed 0.7 gram per denier.

Taking the last of these first, at 9080 grams/inch load divided by 0.7 gram per denier allowable specific stress, the total yarn denier per inch of fabric width must be at least 12971 denier to limit elongation to 0.7%. The middle criteria states that the strength objective can be met with 4×9080 grams/inch divided by 4.25 grams per denier ultimate specific stress for 8546 total denier per inch. Thus, the elongation factor is overriding the strength requirements with the result that $N \times \text{denier}$ must equal or exceed 12971. The first requirement that $K = 23$ also stands. Therefore, $N \sqrt{\text{denier}} = 840$.

Two or three 150 denier base yarns can be plied with 1 or 2 turns of twist to produce a 300 denier or 450 denier resultant yarn. The larger yarn yields a higher production rate on the loom proportional to the square root of yarn denier. Excessive twist reduces yarn strength, hence the low level of ply twist. At 450 denier, cover requires that $N = 40$ yarns per inch. Total denier per inch would be $40 \times 450 = 18000$ denier/inch. Yarn strength is 4.25 grams per denier, giving 76500 gmf per inch or 168 lbs per inch fabric strength. The load is 20 lbs per inch, and the factor of safety, $168/20 = 8.4$, prior to consideration of the benefit caused by increase in the number of yarns per inch after fabric shrinkage. The elongation should be 0.5% at 8 psi.

The weave design for a tubular plain weave repeats on four filling picks. The design requires a four harness cam or dobby loom which when set up on a straight draft will have the following harness motion:

PICK NO. 1 - LIFT HARNESS NO. 1

PICK NO. 2 - LIFT HARNESES NOS. 1, 2, 3

PICK NO. 3 - LIFT HARNESS NO. 3

PICK NO. 4 - LIFT HARNESES NOS. 1, 3, 4

The warp ends are drawn sequentially into sequential harnesses, a straight draft. The loom reed which determines warp end spacing has 19.5 dents (spaces) per inch to allow for loom width-fabric contraction and is drawn four ends per dent (one from each harness). The total yarn density at the reed is approximately 80 ends per inch, accounting for 40 ends per inch in each surface of the flattened tube. Minimum edge distortion is obtained by decreasing the reed draw-in at the outer three dents to 3, 2 and 1 end per dent, respectively. Additionally, filling yarn edge support devices, known in the industry as crowhops, and tension eye pads in the shuttle provide for improved edge uniformity and filling yarn spacing uniformity.

Conclusions

The fabric configuration which offers good appearance with an efficient production rate and exceeds design criteria in strength and low elongation to directly improve fatigue life is as follows:

- 1.) YARN - 450 total denier DuPont Type 56 Dacron (if
plied from 150 denier stock, add 1-2 tpi twist)
- 2.) End and Pick Spacing - 40 yarns per inch
- 3.) Weave design - tubular plain weave.

The governing equations or factors leading to this configuration clearly have some flexibility with respect to yarn size and spacing. This particular configuration offers a factor of safety of 8 using conservative figures and would have longer fatigue life than a fabric construction with a lower factor of safety.

APPENDIX A

Cover Factor

Cover factor is defined as the fraction of total available area in the basic repeating unit of a fabric that is covered by yarn. For woven fabrics, the basic repeating unit consists of one yarn interlacing point, i.e. a yarn crossover. The size of the repeating unit as is shown in Figure A-1 is $1/E$ in length, where E is the number of warp ends per inch, and $1/P$ in width, where P is the number of filling picks per inch.

Basically, the variables E and P are fixed by the loom at certain constant values for any particular fabric. For example, E , the ends per inch, is set by the number of dents per inch in the loom reed at the instant of heat-up. Typical fabrics show about 5% width contraction after passing through the loom temples which results in a similar increase in ends per inch. Thus, while not a true constant, the ends per inch are reasonable constant to within a few percent error once the fabric leaves the loom and the value of E is set by loom configuration. Similarly, P , the picks per inch, are set by loom configuration, specifically the pick gear, and is subject to a few percent error. The amount of error can be related back to the cover factor which this section has as its purpose to explain.

The area covered by yarn is the projected area of the yarns which is obtained from viewing the fabric perpendicular to the fabric plane. Each yarn, warp and filling, has a diameter d_E and d_P , respectively. Their projected areas in the basic repeating unit are $A_E = d_E \times 1/P$ and $A_P = d_P \times 1/E$.

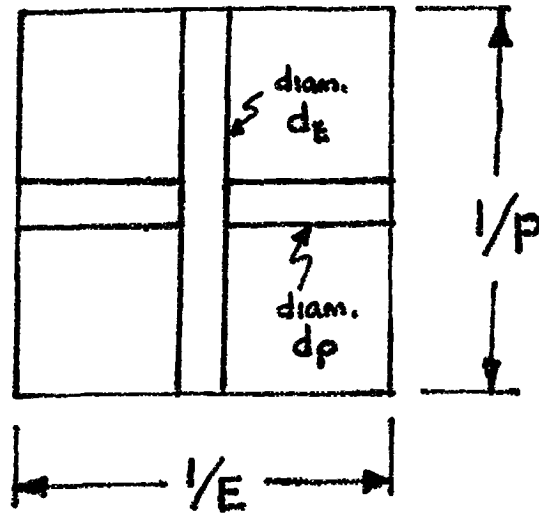


Figure A-1. Fabric Basic Repeating Unit

By definition, the cover factor is:

$$K = \frac{A_E + A_P - d_E d_P}{1/E \times 1/P}$$

The term $d_E d_P$ is shown subtracted in this expression because the yarn crossover area has been added twice to the projected area once each in the A_E and A_P terms.

Empirical research into the relation between yarn diameter and its inverse linear density in the cotton count yarn numbering system led to adoption, particularly with reference to cover factor, of a relation between yarn diameter, d , and cotton count, N_e , as follows:

$$d = \frac{1}{28 \sqrt{N_e}}$$

The symbol N_e is commonly used for cotton count to distinguish it from N_m the metric count, which is determined in metric units. For the

purposes of the remainder of this section the symbols N_E and N_p will be used to refer to cotton count of a filling end or warp pick, respectively.

Cover factor as defined thus far is referred to as true cover factor and is expressed as:

$$K = d_E E + d_p P - d_E d_p EP$$

With diameter replaced by the empirical relation involving cotton count, the expression becomes:

$$K = \frac{E}{28 \sqrt{N_E}} + \frac{P}{28 \sqrt{N_p}} - \frac{EP}{28 \times 28 \sqrt{N_E} \sqrt{N_p}}$$

In practical use, two simplifications of this equation have been made. Firstly, the last term is neglected, and, secondly, a new cover factor is defined by multiplying the expression by 28. With these two changes an expression of the form:

$$K = E / \sqrt{N_E} + P / \sqrt{N_p} \text{ results.}$$

To point out a symbology in which confusion may arise, for those fabrics in which $E = P$, a term N is used to refer to number of yarns per inch in either warp or filling direction. The cotton count is referred to as C.C., resulting in:

$$K = 2N / \sqrt{CC},$$

or if $E \neq P$ and the counts differ:

$$K = N_E / \sqrt{CC_E} + N_P / \sqrt{CC_P}$$

The expressions with either set of symbols (E, P, N_E, N_P) or (N_E, N_P, CC_E, CC_P) clearly are the same and are composed of two parts. A specific reference to warp cover factor in fact refers to the term $K_W = E / \sqrt{N_E}$ and similarly for filling $K_F = P / \sqrt{N_P}$ such that

$$K = K_W + K_F$$

In theory, when the true cover factor is 1.0 or the modified version is 28.0, the total available area is covered by yarn, neglecting the effect of the doubly counted yarn crossover area. Fabrics can be made with cover factor exceeding 28, for example a cotton plain weave duck with total cover of 39 is possible. Below approximately 20, fabrics are very unstable, requiring fillers and binders to constrain the yarns to a fixed geometry. Weaves with fewer interlacing points per weave design repeat such as a twill or satin have higher upper and lower limits of weavability. The reason the upper limit exceeds 28 rests with two factors. The yarns are compressible to a projected diameter less than that predicted by the empirical relation and a subtracted term was neglected, i.e., a fabric woven of circular steel wire would very nearly approach 28 as an upper weavability limit since the wire is essentially incompressible with respect to loom forces.

Cotton count and denier are the two most commonly found yarn numbering systems. A polyester fiber has negligible difference in

specific gravity compared to cotton for which the yarn diameter empirical relation was determined. If the packing fractions are similar the expression for cover factor of a polyester yarn whose specific linear density is given in denier, D , is:

$$K = (E \sqrt{D_E} + P \sqrt{D_P}) / 72.9$$

when $E = P = N$ and $D_E = D_P = D$,

$$K = N \sqrt{D} / 36.5$$

While cover factor cannot be an absolute measure of fabric compactness due to the assumptions and simplifications arising in its derivation, it provides an excellent first trial reference for producing a new fabric. This is particularly true in producing fabrics of comparable appearance, for example, where economics or other necessity may justify a slightly larger yarn woven at fewer picks per inch.

APPENDIX B

YARN AND FABRIC STRENGTH

The measure commonly used in textiles to determine yarn and fabric strength are specific to dimensional measurements of yarns and fabric. Engineering stress in English units is measured in pounds per square inch, psi, the metric SI equivalent being newtons per square meter, N/m^2 . Due to nonuniformity in yarn diameter and, hence, fabric thickness, the textile industry has adopted different measures of these properties. Yarn crosssectional area can be related directly to direct yarn count or inversely to an indirect yarn count. While yarn counts are in fact measures of linear density or inverse linear density, over long lengths an average volumetric density exists. Therefore, for the fixed length of fixed mass, an average diameter also exists, which can be used in determining a specific stress.

For fabrics, which are treated in the textile industry as two dimensional planar sheets, length along an edge times the effective yarn area per unit length measured by means of yarn count determines the specific fabric stress. Optionally, a simple measure of pounds per inch fabric width is used as a stress or stress related value. In fact, because of its simplicity, pounds per inch is a widely found unit of fabric stress.

Returning to engineering stress, and assuming that a yarn is essentially a one dimensional structure, tensile stress in the yarn is

tensile load in pounds divided by yarn crosssectional area in a plane normal to the load, i.e. perpendicular to the yarn axis, or it is tensile load divided by the sum of all fiber crosssectional areas in the normal plane due to macroscopic voids present in all yarns. The yarn crosssectional area is difficult to measure due to a.) uncertainty on the location its outer boundary, being composed of macroscopic fiber elements, b.) irregularity in boundary geometry, being a somewhat randomly determined irregular figure, c.) inconsistency in the boundary shape from section to section in successive slices through the yarn, and d.) nonuniformity in total number of fibers and involved area along the yarn length. Similarly, a count of total fiber crosssections is subject to uncertainty..

The yarn diameter squared is directly proportional to denier and inversely proportional to cotton count, the two most frequently used yarn counts. Yarn crosssectional area, if a circular shape is assumed, is directly proportional to diameter squared as well. The two measures of yarn specific stress are cotton count times yarn load in pounds, the cotton-strength product, and yarn load in grams force divided by denier, the tenacity in gms/den. These are the best simple measures available in ordinary textile usage.

Historically, the count-strength product for cotton yarns has been determined by breaking a skein composed of eighty wraps of yarn, one and one half yards length per wrap, totalling one hundred twenty yards. This value should be consistent in any one class of yarns, typically ranging from 1700 - 2200 for cotton yarns.

For multifilament synthetic yarns, single end strength converted to specific stress in grams per denier is most often used. Attempts to standardize the textile industry on SI units of newtons per tex, where tex is the approved direct count measure, are advancing slowly. The American synthetic fiber/yarn manufacturers use grams per denier to refer to specific stress and tenacity to refer to the specific stress at the breaking load. Some important European researchers have adopted tenacity as a general term for gms/den. or N/tex at any load, breaking tenacity being the term equivalent to the American usage of the term tenacity. Polyester and nylon yarns in the low tenacity range, e.g. textile yarns, have tenacities of 2-3 gms/den, high textile tenacity commonly refers to strength in the 4-6 gms/den range, tire cord quality yarn is of 7 - 10 gm/den, and very high tenacity yarns range from 15 - 30 gms/den. The high strength composites composed of special whiskers or fibers may have a tenacity up to 50 gms/den.

Fabric strength testing most frequently reports strength in pounds per inch width. Load specification for a fabric also is given in lbs/in. The conversion of this figure to a stress value is done on a per yarn basis ultimately so that the stress can be related back to yarn tenacity.

The fabric specific stress, S , in gms/den is determined by dividing the load, P , in grams force per unit fabric width by the product of number of yarns per unit fabric width, N , times the denier per yarn, D . In uniaxial tests of woven fabric, tenacity approaching that of single end yarn tests can be achieved due to the load distribution effect of the crossing yarn set. This effect is quite apparent in that a uniaxial tensile test of a fabric containing forty yarns in the test section, for example, will give strength at break exceeding a test of forty yarns grouped without

the crossing yarn set. Thus, the expression given above:

$$S = P/(ND)$$

can be chosen to have an ultimate value equal to the yarn tenacity. In practice a factor of safety of two to six is included in industrial/commercial applications of fabrics to allow for fatigue, abrasion and other sources of strength loss. That the equation may be subject to error on the order of 10-15% becomes inconsequential with respect to a 200 - 500% factor of safety of design loading to ultimate load capacity.

APPENDIX C

YARN-COUNT-SYSTEMS

The principle function of yarn count systems is to provide a measure of yarn linear density. That all yarns, and particularly yarns being made from natural fibers over the history of yarn count system development, are irregular over a short term basis (inch to inch or yard to yard) led to use of long specimen lengths to find an average value of mass. Long specimen length also allows for mass measurement on devices with lower resolution (fewer decimal places) and, as a result, lower cost. The unit of specimen length is a hank. The number of yards or meters of yarn in a hank is a function of the type yarn being evaluated as well as the system of units being used, e.g. a yard versus a meter.

Two yarn count systems have evolved, firstly, the indirect count systems which are inversely proportional to linear density and the direct count systems which are directly proportional to linear density. Discussion of these two systems follows.

The basic definition of indirect yarn count in English/American units is the number of hanks per pound. The metric count is given as the number of hanks per kilogram. The definition of hank length is given in the following table by count system name.

Table 1. HANK LENGTH IN VARIOUS INDIRECT YARN COUNT SYSTEMS

<u>COUNT SYSTEM NAME</u>	<u>HANK LENGTH</u>	<u>LENGTH UNITS</u>
Cotton	840	Yards
Worsted	560	Yards
Woolen Run	1600	Yards

Woolen Cut	300	Yards
Linen Lea	300	Yards
Asbestos Cut	100	Yards
Typp	1000	Yards
Metric	1000	Meters (Kg mass)

A single yarn evaluated for count in one system may be converted to the equivalent count of another system by using the relation that yarn count times hank length is a constant. The exception is in metric count conversion where use of a hank length of 496.055 yards allow direct conversion with the remaining English system counts.

The history of indirect counts probably would show that cottage spinners could wrap fixed lengths of yarn, and by counting the number of these skeins required to balance against a one pound weight, arrived at the count number in a manner requiring very little technical skill. Typically, counts are given in whole numbers, although one decimal place is sometimes used. Typical spun yarn uniformity would not justify a second decimal place, inferring an accuracy which simply doesn't exist. A peculiarity of indirect yarn counts is the addition of apostrophe and letter s after the number, e.g. the range of counts for commonly spun yarns is 5's to 45's. The count in spoken language retains the s, appearing to be a plural number. There may be some value to this oddity in that nowhere else will a number be referred to as a 12's or 36's.

Worldwide, two indirect count systems predominate. These are the cotton count, given in equations as N_e , and metric count, N_m . Continental Europeans of Western and Eastern Europe and the Russians use metric count. The English, American and Asian textile industries use cotton count, with some crossover in Asia between the two counts.

With international standardization efforts underway stressing recognition of SI units, the accepted standard yarn number is a direct count known as tex. The two common direct counts are denier and tex, denier being the common designation for synthetic fibers and continuous filament yarns (as opposed to the use of indirect count for spun, staple fiber yarns).

The direct counts are determined by finding the number of grams mass per hank, where the tex hank is 1 km in length and the denier hank is 9 Km in length. While a matter more for history, a direct number termed grex using a 10 Km hank length has existed. Additionally, the jute manufacturers of India used a direct English system count called spyndle wherein the number of pounds per 14,400 yard spyndle of yarn was measured. The standardization to tex for all yarns is making very slow progress.

In reporting yarn numbers in denier, whole numbers are used. A single decimal place is used for fiber denier. Generally, an additional decimal place is added for tex numbers, e.g. a 150 denier polyester yarn is equivalent to 16.7 tex. Note that the "s" of indirect counts is not used with direct counts.